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Education matters

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The next two generations of earth scientists

It is great, once again, to bring Members an overview of student research in geophysics for the past year. We have a total of seven PhD, three MSc and eight BSc Honours theses from four states; they represent some excellent work across the spectrum of tectonics, potential field, electromagnetic and seismic projects.

Building for the longer-range future, Andrew Squelch of Curtin University brings us news of the Earth Science Western Australia (ESWA) educational program that educates primary and secondary school students and teachers about our earth, its place in the solar system, its rocks, mineral and hydrocarbon resources.

Geophysics theses in Australian universities in 2018

PhD theses

Wenchao Cao, The University of Sydney: *Global paleogeography since the late Paleozoic: integrating geological databases, plate tectonic models and reconstructions of past mantle flow.*

Palaeogeographic reconstructions are important for understanding the earth's plate tectonic evolution, past marine inundation history of continents, palaeoclimate and to reveal the influence of past mantle flow on the earth's topography. This thesis comprises three inter-connected studies exploring the connections between the earth's surface palaeoenvironments, palaeoclimate, eustatic sea-level change and deep mantle processes by integrating geological observations with numerical earth models over the last ~400 Ma. I developed a new workflow to refine time-varying global palaeogeographic maps by incorporating palaeoenvironmental data from the Palaeobiology Database. Using this approach, the consistency ratio between the palaeogeography and the palaeoenvironments as indicated by the marine fossil collections is increased from an average of 75% to nearly full consistency. The palaeogeography in the regions of North America, South America, Europe and Africa is significantly revised, especially in the Late Carboniferous, Middle Permian, Triassic, Jurassic, Late Cretaceous and most of the Cenozoic.

I investigated the shifting climatic zones for the last ~400 Ma using a comprehensive database of climate lithologies, plate tectonic reconstructions and novel data analysis approaches. The results suggest that the palaeolatitudinal distributions of the lithologies have changed through deep geological time, notably a pronounced pole-ward shift in the distribution of coals at the beginning of the Permian. The changing distribution of coals from the Permian to the present also cannot be considered to have been constant as proposed by previous studies. My results indicate a predominantly bimodal distribution of evaporites over the past ~400 Ma. This suggests that the previously proposed bimodal or unimodal evaporite patterns could have alternated over geological times. The distribution of glacial deposits is consistent with previous interpretations of the main icehouse and greenhouse periods during the last ~400 Ma.

I used time-dependent mantle flow models to interpret the predicted dynamic topography in deep geological time to distinguish between eustatic and regional sea level change signals in the geological record. My results indicate that the trend in global-scale flooding over the late Paleozoic generally correlates with global sea level curves. The first-order flooding history of North America correlates with some estimates of global long-term sea-level change. The flooding lows during the Early Carboniferous and high during the Late Carboniferous for South America are at odds with estimates of eustasy and can be explained by dynamic uplift and subsidence, respectively. According to the numerical models, the reference districts used to reconstruct eustatic curves which are most affected by dynamic topography are those in South China and North America. Therefore, the interpretation of stratigraphic data gathered from these regions should be treated with caution when used to estimate global sea level variations. The studies in this thesis highlight that combining digital palaeogeographic reconstructions, geological observations, plate tectonic motion models and reconstructions of past mantle flow provides insights into understanding the interaction between surface and deep earth processes over geological time.

Maelis Arnould, University of Sydney: *Some surface expressions of mantle convective instabilities.*

The earth's lithosphere, which is the upper boundary layer of mantle convection, represents the interface between the external and internal envelopes of our planet. The multiple interactions between the mantle and lithosphere generate lateral (plate tectonics) and vertical (dynamic topography) deformations of the earth's surface. Understanding the influence of the dynamics of mantle convective instabilities on the surface is fundamental to improve our interpretations of a large range of surface observations, such as the formation of sedimentary basins, continental motions, the location of hotspots, the presence of gravity anomalies or sea-level variations.

This thesis aims at developing numerical models of whole-mantle convection self-generating plate- like tectonics in order to study the impacts of the development and the dynamics of mantle convective instabilities (such as slabs or mantle plumes) on the continuous reshaping of the surface.

First, I focus on the influence of the coupling between mantle convective motions and plate tectonics on the development of dynamic topography (i.e. surface vertical deformations induced by mantle convection) at different spatial and temporal scales. The results suggest that the earth's surface can deform over large spatial scales (>10^4 km) induced by whole-mantle convection to small-scales (<500 km) arising from small-scale sub-lithospheric convection. The temporal variations of dynamic topography range between five and several hundreds of millions of years depending on the convective instabilities from which they originate. In particular, subduction initiation and slab break-off events control the existence of intermediate scales of dynamic topography (between 500 and 10^4 km). This reflects that the interplay between mantle convection and lithosphere dynamics generates complex spatial and temporal patterns of dynamic topography consistent with constraints for the earth.

A second aim of this thesis is to understand the dynamics of mantle plumes and their interactions with the surface. I first characterise in detail the behaviour of mantle plumes arising in models of whole-mantle convection self-generating plate-like tectonics, in light of surface observations. Then, I study how the interactions between surface plate tectonics and mantle convection affect plume motions. Finally, I use observations of the thermal signature of plume/ridge interactions to propose a reconstruction of the relative motions between the Azores mantle plume and the Mid-Atlantic Ridge.

Sarah J. MacLeod, University of Sydney: *Characteristics of extinct spreading centres and the relationship between spreading ridges, hotspots and deep mantle structure.*

Together, oceanic spreading ridges and mantle plumes present the major vehicles through which heat is lost from the deep earth and govern the distribution of almost all basic volcanism observed at the earth's surface. Despite a number of hotspots being located in close proximity to spreading ridges, generally, hotspots are seen to be independent of spreading ridges and a manifestation of 'dynamic' mantle processes, while ridges are considered to be primarily 'tectonic' and their locations not thought to be directly linked to deep mantle convection. This study firstly seeks to improve understanding of the evolution of spreading ridges, by cataloguing the many proposed extinct spreading ridges situated within preserved ocean crust and evaluating their physical and spreading characteristics. Variability of extinct spreading ridges related to tectonic subtype, such as extinct back-arc basin ridges, microplate spreading ridges and extinct large-scale mid-ocean ridges is described, with a comparison with active spreading ridge examples. Uncertain and controversial examples of extinct spreading ridges are compared with the 'characteristic' extinct ridges and this review assists in determining which are more likely to represent former spreading boundaries, as well as identifying a number of possible new ridges that have not been described elsewhere.

The spatial correlation of hotspots with both spreading ridges and subduction zones through time is then systematically assessed, taking into account reorganisations of spreading ridges at times of major ridge jumps, which are identified by preserved extinct spreading centres. This evaluation determines that over the last 100 Ma spreading ridges have been in closer proximity to hotspots than expected by a random distribution, as they are at present-day. After most ridge jumps, spreading ridges are located in closer proximity to a hotspot after the reorganisation, particularly where microcontinents are generated. A different relationship was found for back-arc basin ridges, namely that they were more likely to migrate toward a hotspot after reorganisation only after a duration of spreading of 10 Ma or more and this suggests that large-scale mid-ocean ridges are more likely to be influenced by dynamic upwellings on shorter timescales.

Prior to 150 Ma, spreading ridges appear to have been distributed less extensively than at present- day and a random point on the earth's surface will be up to 50° from a ridge, in contrast with the present maximum distance of ca. 30° from a ridge. This difference could reflect greater uncertainty in reconstructed ridge locations, different active hotspots at earlier times or may be a consequence of supercontinent assembly. In contrast with spreading ridges, subduction zones are generally further from hotspots than expected by a random distribution over the last 100 Ma and this is particularly the case for those hotspots that are likely to have a deep mantle origin. These results support inferences from geodynamic models that deep mantle structure and large-scale convection, driven by subducting slabs, exerts a strong influence on the geometry of deep mantle upwellings, including the plume generation zone.

To better understand the relationship of plumes and deep mantle structure with surface tectonic features, four spherical convection models are evaluated, with three models using a different tectonic reconstruction that provide boundary conditions from plate velocities and subduction zone locations. The first order behaviour and motion of modelled hotspots is then compared with observations of present-day hotspots and their trails. This analysis provides information on the variability of model plume characteristics within and between models and predictions on plume motion in different mantle hemispheres. Large-scale modelled evolution of the large low-shear velocity provinces in the deep mantle is quantified by describing the direction and rate of retreat or advance of the boundaries of the African, Pacific and 'Perm' anomalies. The combined analyses provide insight on the behaviour of plumes and predicted deformation of deep mantle structures, in response to tectonic processes and identifies where the modelled plumes differ significantly from observational data and further refinement of geodynamic models may be required.

Michael Tetley, University of Sydney: *Constraining Earth's plate tectonic evolution through data mining and knowledge discovery.*

Global reconstructions are reasonably well understood to ~200 Ma. However, two first-order uncertainties remain unresolved in their development: first, the critical dependency on a self-consistent global reference frame; and second, the fundamental difficulty in objectively predicting the location and type of tectonic palaeo-boundaries. In this thesis I present three new studies directly addressing these fundamental geoscientific questions. Through the joint evaluation of global seafloor hotspot track observations (for times younger than 80 Ma), first-order geodynamic estimates of global net lithospheric rotation (NLR), and parameter estimation for palaeo-trench migration (TM) behaviours, the first chapter presents a suite of new geodynamically consistent, data-optimised global absolute reference frames spanning from 220 Ma through to present-day. In the second chapter, using an updated palaeomagnetic pole compilation to contain age uncertainties, I identify the optimal APWP pole configuration for 16 major cratonic blocks minimising both plate velocity and velocity gradients characteristic of eccentric changes in predicted plate motions, producing a new global reference frame for the Phanerozoic consistent with physical geodynamic principles. In the final chapter of my thesis I identify palaeo-tectonic environments on earth through a machine learning approach using global geochemical data, deriving a set of first-order discriminatory tectonic environment models for mid-ocean ridge (MOR), subduction (ARC), and oceanic hotspot (OIB) environments. Key discriminatory geochemical attributes unique to each first-order tectonic environment were identified, enabling a data-rich identification of samples of unknown affinity. Applying these models to Neoproterozoic data, 56 first-order tectonic palaeo-boundaries associated with Rodinia supercontinent amalgamation and dispersal were identified and evaluated against published Neoproterozoic reconstructions.

Roger Clifton, The University of Western Australia: *Inversion for depth and forward modelling of magnetically heterogeneous bodies*.

A formula has been derived to provide depth estimates from a greater length of the magnetic power spectrum than by using the classic Spector-Grant formula. Consequently, magnetic depths have been profiled at intervals of 5 km across the Northern Territory, giving depths of up to three bodies at each station. Shallower bodies can be located using flightline data, the ubiquitous interference being addressed by seeking coherent patches in a spread of depth estimates across space and spectrum. Ground work for real-time calculation of interference is set out. Fast modelling of highly detailed bodies using 3-D Fourier convolution is also demonstrated.

Jeremie Giraud, The University of Western Australia: *Integration of geological uncertainty into geophysical inversion by means of local regularisation*.

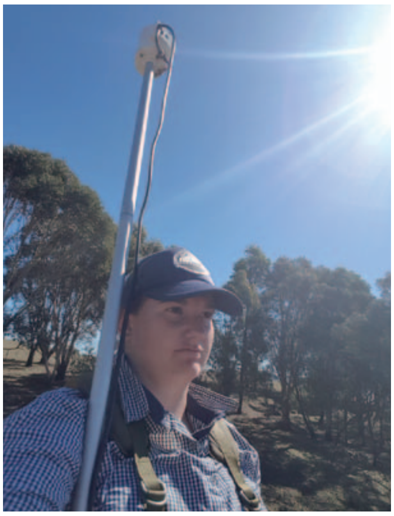
We introduce a workflow integrating geological modelling uncertainty information to constrain gravity inversions. We test and apply this approach to the Yerrida Basin (Western Australia), where we focus on prospective greenstone belts beneath sedimentary cover. Geological uncertainty information is extracted from the results of a probabilistic geological modelling process using geological field data and their inferred accuracy as inputs. The uncertainty information is utilised to locally adjust the weights of a minimum-structure gradient-based regularisation function constraining geophysical inversion. Our results demonstrate that this technique allows geophysical inversion to update the model preferentially in geologically less certain areas. It also indicates that inverted models are consistent with both the probabilistic geological model and geophysical data of the area, reducing interpretation uncertainty. The interpretation of inverted models reveals that the recovered greenstone belts may be shallower and thinner than previously thought.

Heta Lampinen, The University of Western Australia: *Basement architecture for the polymetallic sediment-hosted Abra (cadabra)*.

The 1590 Ma polymetallic Abra deposit, 170 km south west of Newman in Western Australia, is adjacent to an orogen parallel listric fault and hosted in Mesoproterozoic sediments. The Edmund Group sediments cover a fairly unknown Archean to Paleoproterozoic basement architecture, which must have controlled the mineral system resulting in the Abra deposit. Geology constrained combined gravity and magnetic forward modelling across the deposit was carried out to understand the composition and the architecture of the mid-crust (4–10 km) at the deposit. Results suggest an anomalously dense and magnetic mid-crust composition in the intersection of the orogen parallel listric faults and a possible intersecting vertically accretive basement structure.

MSc theses

Stephanie Hawkins, Macquarie University: *Investigating an igneous dyke swarm using applied field magnetics.*



Did rifting on the eastern coast of Australia produce igneous rocks on either side of the Sydney Basin? A dyke swarm near Oberon in central-western New South Wales has been investigated using magnetics to determine its relationship to the Permian-Cretaceous rifting that allowed the extensional rift basin that became known as the Sydney Basin to deposit unconformably on top of the Lachlan Fold Belt. A secondary research question addressed is that of the relationship between the granites and the dykes themselves, and whether they are related or independent events. This research uses magnetic modelling of the Edith dyke swarm from aeromagnetic data and from a ground traverse magnetometer survey. Magnetic modelling was completed using ModelVision 15.0 and shows groups of thin (~4–8 m thick), vertically dipping tabular bodies successfully fit the anomalies. The modelling is accompanied by analysis of thin sections from a section of the swarm along Fish River at Evan's Crown Reserve, as well as geochemical data from a previous thesis analysing a portion of the swarm outcropping around Tarana. Both these locations are around 35 km north of the survey area, and represent the northern reaches of the dyke swarm. This project has combined geophysical modelling with geochemical data to understand the structures causing the north-south striking magnetic anomalies that intrude the Carboniferous Bathurst Batholith.

Alice Van Tilburg, Macquarie University: *Exploring lithospheric scale structure in the Eastern Yilgarn Craton with 3D magnetotellurics.*

The electrical structure of the Eastern Yilgarn Craton is of interest in building understanding of the pathways for mineralisation at the lithospheric scale. This project uses three dimensional inversion of magnetotelluric data from both broadband and long period stations to investigate an east- west traverse of the Youanmi and Kalgoorlie terranes. These data are from the Southern Cross Magnetotelluric Survey. Previous studies in the region focus on two dimensional modelling, however, phase tensor analysis of these data show a predominantly three dimensional subsurface that varies in strike across the profile. Models were produced using 26 stations from the Southern Cross data set, and show several conductive regions spanning a predominantly resistive subsurface.

Joshua Grover, The University of Melbourne: *Palaeogene – Neogene deep lead sediments of the Stawell Zone: Evaluation of geophysical techniques for mapping deep leads.*

Deep lead sediments, known for their relatively large abundances of alluvial gold and potential for groundwater flows, were deposited in the Stawell Zone throughout Palaeogene-Neogene, when extensive palaeodrainage systems eroded through substantially older Cambrian bedrock. They were subsequently overlain by Quaternary sediments until recent re-exposure at the surface from erosional processes. The distribution of deep leads has been approximated using the Victorian Aquifer Framework (VAF), which interpolates drill hole data from mining records and groundwater databases from as early as the 1880's. This study aimed to rectify the key shortfall of the VAF – irregular spacing of drill holes – and improve the constraints on the model by using geophysical data to image the geometry of deep lead palaeochannels in the subsurface.

High-resolution land-based gravity as well as horizontal to vertical spectral ratio (HVSR) passive seismic datasets were acquired near Stawell, western Victoria. Geophysical interpretation of passive seismic data was found to accurately image the geometry of the deep lead palaeochannels, as well as differentiate between the Palaeogene – Neogene deep lead sediments at the base of the overlying Quaternary cover sediments. Conversely, it was not possible to identify the response of the deep lead sediments in the land-based gravity data, attributable to a lack of density contrast between the fill and cover sediments within the palaeochannels and the surrounding Cambrian bedrock. Because of the success of the HVSR method, further application of this form of geophysical data to enhance mapping of deep lead sediments may reduce the need for expensive drilling projects. This may increase economic viability for mining companies to target alluvial gold deposits, as well as improve access to groundwater, as the distribution of deep lead sediments becomes more accurately identified.

BSc Honours Theses

Adrian Eiffe, University of Adelaide: *Assessing Geophysical Model Uncertainty: Bootstrap and Pareto-Optimal Approaches.*

This project was undertaken to gain a greater understanding of what we can learn about the conductivity structure within the earth's crust from ground-based measurements. We can measure the effects of telluric currents induced under the surface, and learn about the conductivity beneath with this information. However, there are limitations to how well this can be achieved. The MT technique is preferentially sensitive to more conductive structures, where current densities are highest. Surface measurements are of finite bandwidth and subject to random noise. They cannot be mapped uniquely to a single best model. Instead, an infinite range of models are consistent with the measurements, to a degree defined by the error of the measurements taken. The first aim of this project was to investigate what could be learned from a single set of MT data by applying a bootstrap resampling approach. By resampling the original data, a group of subsets of the data are obtained, from which we can produce new models. These models should be sufficiently independent to apply some simple statistics and assess the sensitivity of the model to the data. The second aim was to investigate how the integration of two EM surveying techniques that measure the same physical property of resistivity can be used to better constrain the produced models, reducing the issues of non-uniqueness.

The bootstrap resampling method is shown to be highly effective as it can be run in parallel with little additional computational cost. We show that suites of two-dimensional inversions with subsets of data can effectively provide insight into the uncertainty of different regions of a model. The approach is scalable to any dimension, and easy to implement. We demonstrate the utility using a 100 km long transect of 55 stations spaced approximately 2 km apart collected in the Curnamona Province, on the border of South Australia and New South Wales. Secondly, we demonstrate a proof of concept for using a Pareto-optimal approach to determine the overlapping acceptable model spaces of two EM techniques (MT and time domain EM), thus narrowing the range of determined model parameters. The combination of defining model uncertainty for one technique and reducing the model space using two techniques should significantly increases the confidence that the resulting models are representative of the real earth.

Robin Keegan-Treloar, Flinders University: *A multi-method hydrological study of Wither Swamp, in the Fleurieu Peninsula, South Australia*.

Springs are a crucial source of water to wetlands and are often sensitive to drought cycles and changes in groundwater conditions. To effectively manage spring dependent wetlands there are three essential components to be considered: (1) the quantity of water discharging from the springs; (2) the origins of the waters contributing to the springs; and (3) the subsurface controls on the spatial distribution of the springs. This study applied several temperature-based, hydro-geophysical and hydro-chemical techniques to assess these three fundamental components of Wither Swamp, a spring dependent wetland system in the Fleurieu Peninsula, South Australia.

Analysis of water samples suggested that the springs derive water from a mixture of precipitation and groundwater. This finding was supported by geophysics, which indicated that the groundwater likely flows from a fractured rock aquifer into an overlying clayey sand layer where the groundwater mixes with recent rainfall. Springs were present in downslope regions where a clayey sand material breached an uppermost peaty clay layer. Three independent methods estimated the spring flux to be upwards on the order of 10^{-6} m/s. As aquifers have a large storage capacity, groundwater may provide a vital source of water to Wither Swamp during periods of drought, ensuring the continuance of essential plant and animal habitat.

Emily Birrell, Monash University: *Significance of the Emu Shear Zone, Yilgarn Craton, Western Australia.*

The Emu Shear Zone is located in the Yilgarn Craton in Western Australia, one of the largest exposed sections of Archaean granite-greenstone terrane. The Yilgarn Craton is divided into a series of terranes and then further into domains by regional NNW trending faults and shear zones on the basis of distinct geological characteristics. The Emu Shear Zone, with a length of ~120 km, divides the Gindalbie domain to the west, and the Menangina and Bulong domains to the east and south-east of the Kurnalpi Terrane. Despite the Emu Shear Zone being a major NNW trending structure, there are limited structural observations and interpretations available regarding the geology of the system, with a major restraining bend associated with the shear zone only recently being identified in newer, higher resolution aeromagnetic images. Defining the structural evolution and kinematics of these major structures is important not only to determine potential constraints for gold mineralisation in the region, but also in reconstructing the tectonic evolution of the Yilgarn Craton.

A multi-scale approach was used for this study, combining geophysical interpretations, outcrop observations and thin section analysis with a focus on three locations; Camel Dam, Vertigo and North Brilliant. The restraining bend is shown to have three major splays. The easternmost of the three is the master shear zone, and is a major site of dilation allowing a large amount of fluids to migrate through the system. Hydrothermal alteration of host rock can be seen along all three splays, and likely resulted due to an increased permeability during deformation. Si and Fe-rich fluids resulted in the quartz-hematite banding seen in outcrop, with a sometimes ‘cherty’ siliceous appearance leading previous observations to believe this fault rock was a sedimentary unit. The Emu Shear Zone formed early in the regional deformation history, with the restraining bend evolving during a major NW-SE shortening event. This resulted in predominantly sinistral movement across all three splays, with the exception of dextral movement in Camel Dam. A dextral re-activation then resulted in hydraulic brecciation, and a minor sinistral shearing occurred during the final deformation event. Based on results collected during this study, it is theorised that gold mineralisation is most likely to occur in Vertigo, in the N-S oriented fault bend. This is due to the locality of the shear zone having a wide dilational potential, with over a kilometre of wide quartz-hematite banding seen. It is also suggested from results that gold was deposited during a D4 event, which is later than the principally D3 mineralisation recorded in literature for the Yilgarn Craton.

Christina Boundy, Monash University: *Structural Controls Influencing the Emplacement of the Dargo Tonalite, Using AMS, Geochemistry and Gravity*

Anisotropy of magnetic susceptibility, geochemistry and gravity were used to study the Dargo Tonalite, a late Silurian

– early Devonian intrusion located in the Tabberabbera Zone in eastern Victoria. Studying this intrusion is significant, because the orientation of the pluton not does not fit the pattern of the many other intrusions in the broader area of the Lachlan Fold Belt. By analysing the geochemistry of the igneous rocks, a deep source of melt has been indicated, as well as an association with subduction processes and the fractionation of the melt. It is suggested in this thesis that the multiple deformation events in this region have created crustal scale structures that allow the transportation of deep melts, as well as shallower features that have influenced the plutons orientation during emplacement in the upper crust. The structure influence the Dargo Tonalite orientation would have formed during the Bindian event in the early Silurian.

Matthew Paul Burgess, Monash University: *Archean magmatic evolution: LA-ICPMS U/Pb and trace element analysis of zircons from the eastern Yilgarn superterrane.*

Field mapping was undertaken 19 km NNW of Kalgoorlie-Boulder, Western Australia, at the Scotia-Kanowna dome, the core of which is an Archean TTG-affinity high-Ca monzogranite batholith. Numerous quartz-phyric porphyry intrusions protrude from the batholith proper into the surrounding greenstone stratigraphy and are associated with NW/SE trending dextral faults. Geophysical and geochemical datasets, and field reconnaissance indicate a magmatic-hydrothermal transitional environment conducive to Sn, W, Cu, Au and Mo mineralisation, extending N-S from the batholith proper. These observations are characteristic of Intrusion Related Gold, Porphyry Cu-Mo-Au and Orogenic Au systems. Further study of the field area is warranted to constrain which system is prominent. During field mapping, first order, low angle ductile fabrics within quartz porphyry units at the southern dome margin were identified. This D1, ENE/WSW shortening event has been regionally dated to 2680 Ma, consequently this field observation suggests these porphyritic intrusions have been emplaced prior to the Scotia batholith, which has been thrice dated by sensitive high-resolution ion microprobe to 2660 Ma. Representative samples were collected for whole rock geochemistry and laser ablation – inductively coupled plasma mass spectrometry (LA-ICPMS) for U/Pb and simultaneous in-situ trace element analysis. Cathode luminescence enabled scanning electron microscopy of 248 zircon grains collected from both units reveal homogenous, clear, inherited zircon cores within significantly recrystalised oscillatory zones, some sector zoning and metamorphic rims. Of the 581 laser points analysed, the inherited cores were the only concordant (>90%) U/Pb datapoints across the U^{238}/Pb^{206}, U^{235}/Pb^{207} and Pb^{206}/Pb^{207} isotopic systems, yielding an approximate inherited age population of 2791.8 Ma (±4.3, N: 31).

Trace element analysis and Ti-in-zircon thermometry of these inherited cores demonstrate protracted growth within the feldspar stability field at approximately 650˚C from a reduced, HREE enriched magma with a consistent, negative Eu/Eu* anomaly (<0.7), and a low Ce/Ce* anomaly of (<30). The oscillatory growths enveloping the cores are increasingly affected by Pb-loss and increasing Pb^{206}/Pb^{207} disconcordance. However, the REE signatures, and Th/U ratios evolve coherently from the innermost oscillatory rims, outwards. An Eu/Eu* anomaly (consistently >1), increasingly positive Ce/Ce* anomaly from 50 to 250, and complete HREE depletion, suggests increasingly oxidised, prograde conditions reaching 950°C, describing a complete transition of the magma from the feldspar to garnet stability field. The most coherent population from this prograde environment (>80% concordance) are the innermost oscillatory zircon growths, at 2694.2 Ma (±3.6, N: 26). Beyond these inner oscillatory growths, the U/Pb isotopic system becomes decoupled.

The geological transition that these zircons record indicates periods of fertility for both the Intrusion Related Gold system and the Porphyry Cu-Au model. It also coincides with the protracted period of continental rifting, east-west extension, mafic and ultramafic volcanism that are accepted to have commenced earlier than 2720 Ma in the Kalgoorlie Terrane, and have terminated by 2692(±4) Ma. This zircon record begins in the lower continental crust, within an extensional setting, likely an evolving back-arc basin. The continuously prograde conditions can then be explained by either lower crustal/mantle interaction encouraged by the weakening continental crust and protracted volcanism, interaction with exsolving fluids from de-watering of hydrous subducted mafic material, or a diapiric mechanism whereby this section of lower crust descends and assimilates with the upper mantle.

Mrinal Denis Deane, Curtin University: *Derivation of seismic sequence attributes from VSP data as proxy lithological parameters for Harvey, WA.*

The South West Hub Project is an initiative of The Government of Australia and The Government of Western Australia to counter carbon emissions through Carbon Capture and Storage. The Lesueur Sandstone formation of the Perth Basin has been identified as a potential CO_2 reservoir. The formation is close to the surface, through an uplifted block, near the town of Harvey in Western Australia. The interpretations from geological and geophysical data revealed that no conventional seal is present, but other trapping mechanisms like palaeosols might exist that slow down CO_2 migration.

This thus, became of great importance to characterise both the reservoir and overlain sedimentary sequence in terms of shale/sand volume that is likely to play a crucial role in slowing down upward migration of injected CO_2. To advance our understanding of the Yalgorup member that overlays the reservoir – high-density 3D seismic, Vertical Seismic Profiling (VSP) and borehole seismic measurements were acquired by Curtin University at Harvey 4 and Harvey 3 wells. The later one is the subject of this study. These data provided a possibility for an in-depth study of Yalgorup.

Vertical Seismic Profiling (VSP) measurements showed a sudden variation of both quality factor (Q-factor) and total energy which correspond to an increased shale volume just above the Wonnerup member. These observations inspired my investigations with the final aim of extrapolating it away from the borehole. One way of doing so was through the utilisation of seismic attributes that can be computed from the 3D surface seismic data and have a relationship to VSP observations. However, such attributes have to be robust enough to allow their computation not only on the high-resolution 3D surface seismic data around Harvey-3 well but also across a large area covered by the regional 3D seismic data.

Thus, the choice was seismic sequence attributes as they allow averaging of wavefield properties over a selected sequence that is the time interval. The investigation then reduced to the selection of the relevant sequence attributes that may be used to separate shaly from sandy intervals or equivalently determine the spatial extent of the palaeosols and in that way characterise the CO_2 holding or 'sealing' capacity of Yalgorup member.

The final methodology adopted was to compute the sequence attributes first on the transmitted VSP wavefield and select the specific attributes, called 'proxies', which correlated attenuation measurements and stratigraphy derived from borehole logs of H-3 well. Three attributes were identified from the VSP analysis – Energy half time, Effective Bandwidth and Zero Cross-Frequency which showed some relationship to the volume of palaeosols. These attributes were subsequently computed on 3D seismic data with the help of interpreted 3D horizons.

Anomalous attribute values were found for a thicker (in terms of spatial extent) unit of palaeosol above the Wonnerup member that corresponds to a high attenuation zone determined from the transmitted VSP wavefield. The resultant attribute maps showed a good correlation with the Harvey-3 logs. This methodology may be applied to the regional seismic cube to enable the creation of an improved static model and subsequent CO2 injection simulation studies.

Alejandro Sanchez, Curtin University: *DHI for gas prospecting and lithology discrimination for the Otway Basin (Victoria).*

The Port Campbell Embayment Area is the most important gas producing region in the onshore portion of the Victorian sector of the Otway Basin. In the last century, more than one hundred exploration wells have been drilled in the region, which resulted in the discovery of nineteen natural gas and CO_2 fields. As is typical for gas bearing sediments, the prospective drilling sites were identified based on intense seismic amplitude anomalies –bright spots –at the target interval.

We believe that the success rate of the drilling and effectiveness of the production might have been improved if a more advanced seismic characterisation had been done. This thesis project focuses on quantitative seismic characterisation of the Eastern part of the Port Campbell Embayment Area, which has accumulated extensive set of geological and geophysical data thanks to the Otway project –the main Australian in-research project for carbon dioxide storage. We use data from seven petroleum wells and one CO_2 geo-sequestration well, in conjunction with a post-stack time migrated three-dimensional seismic volume. Having these data, we performed acoustic impedance inversion, rock physics transforms, and seismic modelling to study the feasibility of using bright spot amplitude signatures in the Waarre Formation for gas prospecting and lithology discrimination.

Our workflow began with seismic to well correlation, where satisfactory ties were obtained at the target interval – the Waarre and Eumeralla Formations. Secondly, we created low frequency models for post-stack acoustic impedance model-based inversion, and iteratively excluded one of the wells from the model generation to validate the robustness of the model and set up its parameters. The second important component of the seismic inversion –seismic wavelet – was obtained through an iterative process: (1) extract a statistical wavelet at the target interval for each well, (2) extract a Roy-White wavelet at the well with the highest seismic to well correlation quality, (3) obtain the final wavelet through an inverse modelling. We inverted the data and obtained an absolute acoustic impedance volume that yielded global P-impedance and seismic misfits of 545.5 (m/s) (g/cc) and 6.97% respectively at the well locations. Later, we carried out fluid substitution and seismic modelling to analyse the effect of gas saturation and reservoir thickness in seismic amplitudes, and created crossplots to study the behaviour of porosity and seismic properties of the Waarre sediments with depth

During the inversion stage, we found that deterministic post-stack acoustic inversion can be effectively utilised to estimate the acoustic impedance changes at the Belfast-Waarre and Waarre-Eumeralla interfaces, where it was observed that the Waarre Formation is characterised by a strong decrease of the absolute acoustic impedance with respect to the overlaying Belfast Mudstone.

Our rock physics analysis suggests that acoustic impedance inversion can be utilised for porosity computation, sand prediction and the identification of potential gas reservoirs at the Waarre level; having a post-production well, CRC-1, helped us to verify the rock physics model for the formation. Lastly, we showed that the application of relative acoustic impedance cut-off filters resulted in the prediction of sand geobodies and identification of at least five gas prospects.

From this project we concluded that, even though there are challenges posed by the fact that the seismic data was acquired onshore and that the imaging flow might have been imperfect, quantitative seismic interpretation methods showed to be valuable for reservoir mapping, lithology discrimination and the identification of potential gas reservoirs in the Waarre Formation.

Anshuo Yang, Curtin University: *Depth to the basement estimate from seismic data – a comparative study.*

Seismic reflection method can provide very precise images of the underground. One of the key issues is that this method becomes more expensive as the target under investigation becomes shallower. Hence this study investigates the potential of alternative seismic methods as well as the utilisation of other than the primary (P) waves to characterise the near surface at Ravensthorpe mine site. The results are to be compared to a more conventional P-wave reflection survey. Our study deploys reflection, refraction, and Multichannel Analysis of Surface Wave (MASW) along a pre-selected transect. Three different types of sources: 45 KG weight drop, shear plate and Betsy gun were recorded by three different receiver types: 3C geophones with spikes, single component nodal geophone acting as a buried receiver and optical fibre. Data processing included P-waves in vertical component, as well as P-wave with converted SV-wave in in-line component and Raleigh (R) waves. Each wave mode samples the underground differently as its propagation is governed by different equations. Hence joint analysis of these waves might have a potential to better characterise complex near surface at Ravensthorpe where both geological and geotechnical information are needed for optimisation of mining operations. My objective was to create accurate images of near surface structures that can provide information on the basement depth, structures and discontinuities and lithology that is rock properties. Each method utilised is evaluated against these objectives. The study also aims to assess the effectiveness of each method in terms of execution time, expenses related to the field operations, degree of operation difficulty.

Data processing included all body waves and reflection, refraction and inversion methods. Reflection survey in both vertical component and horizontal component with 45 kg weight drop showed significant depth of penetration (over 400 m). However, data processing is not trivial and requires very accurate static corrections and velocity field estimation in the regime of low signal to noise ratio (SNR). The mix of P-wave and SV-wave reflected images are also processed and analysed (P-S-S-P mode). P-wave refraction data processing included plus-minus method, Generalised Reciprocal Method (GRM), and refraction tomography. Produced P-wave velocity field is evaluated together with the S-wave velocity field produced from the inversion of surface waves (MASW method). Inverted P-wave velocity field provides information within first 100 m while S-wave field covers 1/3 of that depth. Two wavefields correlate well over first 20–30 m. Joint analysis of all waves help delineate several structural features. The combined value of all methods exceeds each individual approach. Hence near surface investigations should be optimised for all wave modes but conducted efficiently at minimal expense.

Highlighting the importance of earth sciences in our schools

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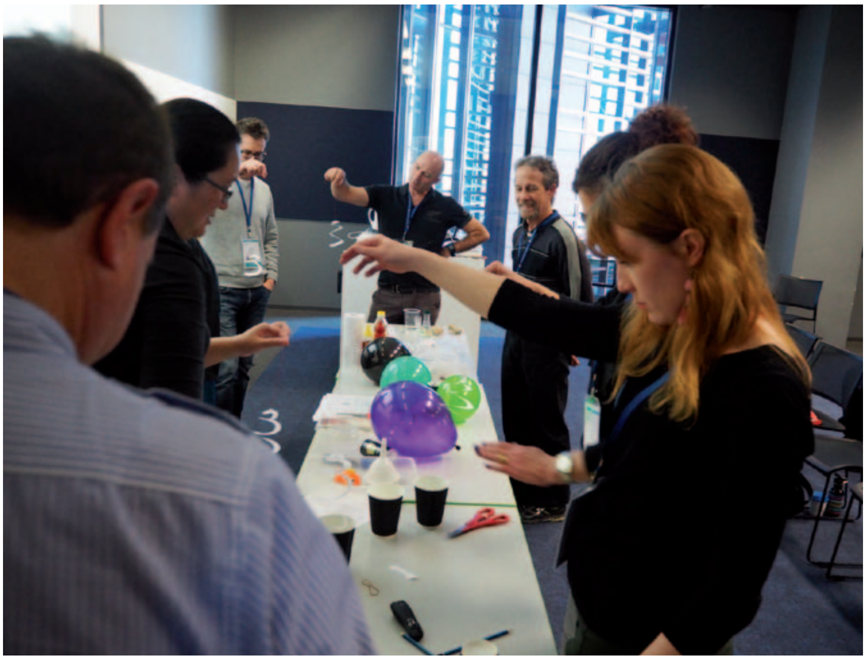
Earth Science Western Australia (ESWA) continues to improve the quality of earth sciences and STEM education for students, teachers and the wider community. This exciting and important work is possible thanks to the long-standing support of a number of organisations, such as the Australian Society of Exploration Geophysicists.

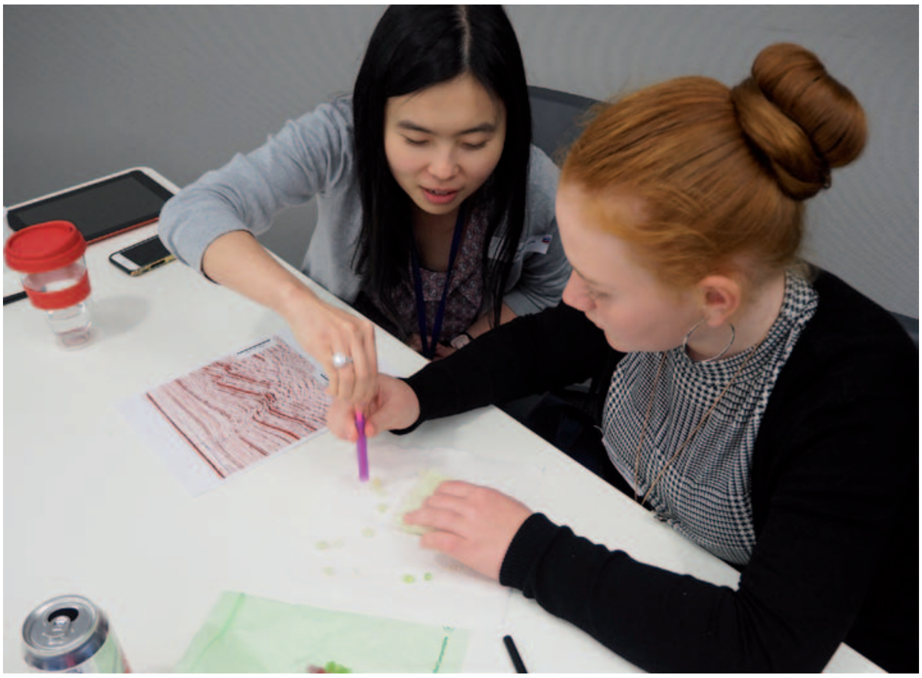
ESWA works to create, produce and deliver innovative, valuable earth sciences education materials and experiences. Geophysics is included where it fits best with several activities across the Year 7, 8, 9 and 12 curricula. Education materials are all curriculum-linked and promote student engagement. These include teacher resource packages full of hands-on activities and online interactive exercises. For senior school students, ESWA has produced textbooks for Earth and Environmental Science, as well as geological field guides for Perth and the Capes region of south-west WA. In support of these materials, ESWA delivers engaging and hand-on incursions across Western Australia and geological field activities across Perth, the south-west and Kalgoorlie. In 2017 alone, 5102 students, from Kindergarten to Year 12, were engaged in these activities.

To ensure the earth sciences materials that are produced are implemented in the best possible way, ESWA provides professional development opportunities at teaching conferences, network meetings, school development activities and special events. As a result of this extensive engagement 1636 teachers were involved in professional development with ESWA in 2017.

Increasing awareness of the wide range of careers opportunities that earth sciences



Teachers explore aspects of planetary science, including convection currents and static electricity, at a primary workshop at the Conference of the Australian Science Teachers' Association.



Staff and students explore for oil and gas in activities run by ESWA.

provide is vital to ESWA's core business. In pursuit of this they provide careers-based incursions for students in secondary schools. They assist with and run related events in which geophysics is presented as a career opportunity for the benefit of students showing interest in learning more of our science.

With a growing focus throughout education and the resources industry on STEM education and skills ESWA continue to strive to further the recognition of earth sciences as an integral part of STEM. This has been grown through the creation of earth sciences-based STEM project packages.

If you are keen to learn more about what is happening in this space or to partner with ESWA please visit www.earthsciencewa.com.au for more information.

Students at Ashdale Secondary College, Perth, work together to classify a rock collection.